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INSTALLATION AND OPERATIONAL RESULT OF LINDARC™ REAL TIME LASER OFF-GAS ANALYSIS SYSTEM AT ACCIAIERIE BERTOLI SAFAU - ABS (ITALY) ELECTRIC ARC FURNACE*

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Abstract

In today's highly competitive market situation, it is of outmost importance for EAF steel makers to optimise their processes in order to reduce operating costs and to improve safety and reliability of the equipment. The laser based off-gas analysis technology, With laser units installed on the fix duct, downstream the combustion gap, uses the "Tuneable Diode Laser Absorption Spectroscopy" (TDLAS). The system performs real-time off-gas emissions measurements of CO, CO2, O2, H2O and temperature. A closed-loop operation is in place for dynamic control of the chemical energy package combustion/post-combustion of CO, H2 and CH4 gases into the EAF furnace shell. A statistical framework which builds on a data analysis engine, based on Danieli Automation Q3Intelligence technology, evaluates the "fingerprint" of the process represented by average and deviation trends of both gases and other process parameters. Process fingerprinting is conceived both for off-line profile optimisation and on-line control of the refining process. This paper describes how the technology has been applied and the results achieved at ACCIAIERIE BERTOLI SAFAU (Italy) 100 t AC Electric Arc Furnace.

Keywords: EAF off-gas; Post-combustion; Chemical energy; Process control.

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1 FUNDAMENTALS

Each molecule has a unique energy storage structure that determines its absorption spectrum. Molecules in the gas phase store internal energy in three modes: electronic, vibrational, and rotational. A molecule can change from a lower energy state to a higher one (energy transition) by absorbing a photon, whose energy is determined by its wavelength. When the photon energy matches the difference between two molecular energy states, the photon is absorbed. Several gas molecules can absorb photons at specific resonance frequencies (single absorption lines), in this case the produced molecule energy transition leads to a signal reduction on the receiver only at that particular frequencies. The amount of energy absorbed – signal reduction is ruled by the Beer Lambert Law and it depends, among other parameters, also on the absorbing molecules concentration and the optical path length (distance travelled by the laser beam inside the absorbing gas mixture.

The LINDARC™ system uses the TDLAS (Tuneable Diode Laser Absorption Spectroscopy) together with the WMS (Wavelength Modulation Spectroscopy) technique. For each measured gas the absorption line is carefully chosen inside the NIR (Near Infrared Range) and Extended-NIR to avoid cross-response with other gases present into the off gas mixture.

The laser diode is able to emit a monochromatic light with a spectral band which is considerably narrower than the gas absorption one; by varying the diode laser current and temperature, the light wavelength is scanned across the absorption line and even on both sides of it, where the specific gas does not absorb. The light detected in this non-resonant region is used to create a baseline absorption that includes the dust particles absorption/scattering effect, meanwhile the light detected inside the gas absorption region includes the signal reduction due to both dust particles and selected gas molecules. Comparing the two absorptions the system is able to single-out the gas-only share and thus to measure its concentration. The light is scanned across two different absorption lines of the same selected gas and the two absorption lines are compared to calculate the gas temperature.

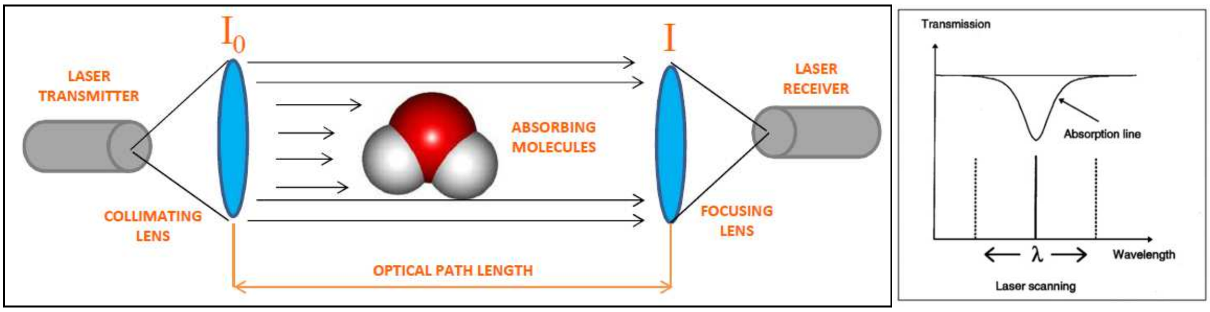

Figure 1: Tuneable Diode Laser Absorption Spectroscopy – TDLAS.

The dust does not affect the measure quality as long as a minimum light intensity is able to reach the receiver. Once the transmitted light drops under a certain critical value the measure becomes not reliable or even not available. Previously presented papers [1,2] have already described in detail the physics principles and the TDLAS laser detection technique; all previous experiences by others companies in this application [2-5], have been of high importance for the success of ABS project.

Currently, the LINDARC™ off-gas analysis technology has a working range as described in Table-1 here below:

Table.1: LINDARC^{TM} system features.

O_2	0 ÷ 25%	In temperature range between 0 ÷ 1600 °C (32 ÷ 2912 °F)
CO	0 ÷ 50% 0 ÷ 100%	In temperature range between 400 ÷ 1000 °C (752 ÷ 1832 °F) In temperature range between 1000 ÷ 1600 °C (1832 ÷ 2912°F)
CO_2	0 ÷ 100%	In temperature range between 400 ÷ 1600 °C (752 ÷ 2912 °F)
H_20	0 ÷ 50%	In temperature range between 600 ÷ 1600 °C (1112 ÷ 2912 °F)
Off gas temp.	400 ÷ 1600 °C (752 ÷ 2912 °F)	
Response time	2 s	

1.1 Acciaiere Bertoli Safau (ABS) AC - Electric Arc Furnace

Acciaierie Bertoli Safau-ABS produces a wide range of special engineering steels, in quality and dimensions. The plant is equipped with two melting lines. The first one consists of a 100t AC electric furnace whereas the second one features a 100t DC electric furnace. The LINDARC™ off gas analysis system has been installed in the AC furnace that, since 2007, is equipped with MORE chemical package (Figure 2). The furnace is equipped with a supersonic water cooled door lance manipulator for cleaning purposes and with CATFIS temperature/sample manipulator.

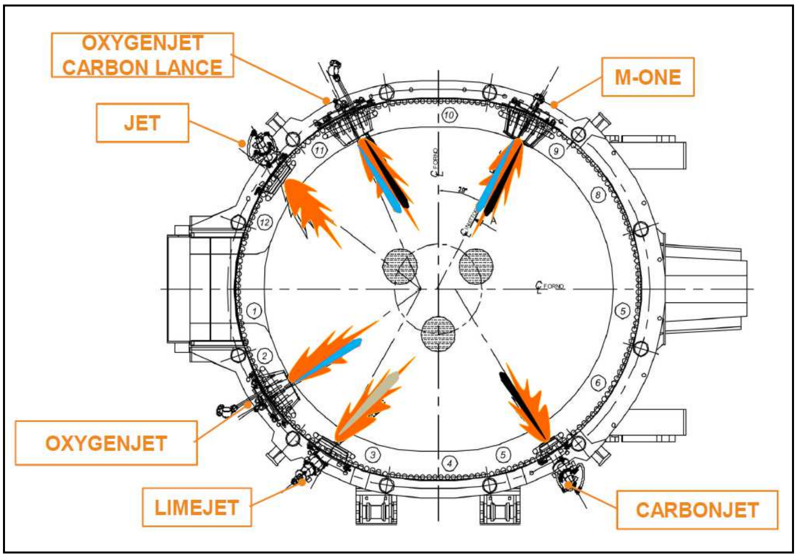

Figure 2: AC EAF injectors layout

The furnace main features are:

EAF Type	AC Spout
Panels ID:	5330 mm (17' 5-27/32")
Electrode diameter:	610 mm (24")
Transformer:	75 MVA
Tap weight:	100 t (110 st)
Burner	6x3 MW
Supersonic oxygen injection:	1x1500 Nm^3/hr [939scfm] and 2 x 1300 Nm^3/hr [840scfm]
Injected carbon:	2x22 kg/min [49 lb/min] and 1x20 kg/min [46lb/min]
Charged carbon:	Bucket and through the roof 5th hole
Injected lime:	1x150 kg/min [332 lb/min]
Charged lime:	Bucket and through the roof 5th hole
Bottom stirring:	3xN_2 porous plugs
LINDARC™ features:	CO, CO_2, H_2O and Temperature (2 laser units)

1.2 LINDARC™ Off-Gas System Installation

Laser off-gas analysis technology is installed just downstream the combustion gap, on the water cooled duct, to analyse the off-gas which is drawn off from the furnace 4th hole (Figure 3). To guarantee that the measurement deals only with the EAF off-gas, free from any dilution effect due to the secondary air entering through the gap, the location and the length of the measurement path is carefully selected. To accomplish this task, specific CFD simulations (Figure 3) have been performed in the melting and the refining phases, in this way the dimensions and location of the hot gas stream has been determined, allowing to place the measurement path just right into its core. Two water-cooled fingers, protruding inside the off-gas duct, have been installed to "shield" the laser beam up to the un-contaminated core of the hot off gas stream. These fingers are water cooled and kept clean by neutral purging to avoid interference with the off gas concentration measurements.

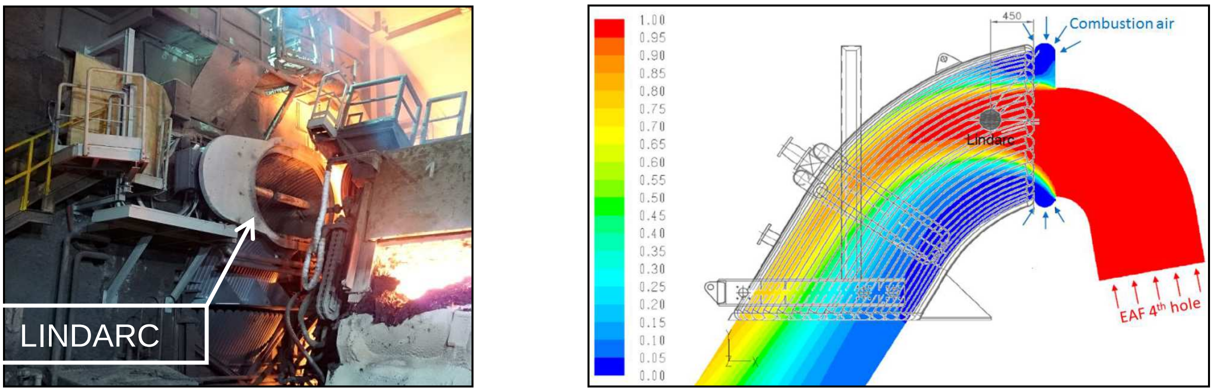

Figure 3: On-field LINDARC™ installation with the hot gas stream simulation.

The laser transmitter and receiver are located, in-line with the water cooled fingers, right outside of the duct and are protected with a heavy duty housings (Figure 4) to prevent any damage due to the very harsh environment typical of this location.

Figure 4: Receiver unit mounted outside the water cooled duct.

Figure 5: Control cabinet outside the dog-house

The cooling element and purging gasses are all managed by a dedicated cabinet located in an accessible and safe location away from the EAF (Figure 5). This cabinet is equipped with valves and instrumentation to control and measure all media used by the system. Included in the cabinet there is also a membrane dryer to guarantee the best air quality and prevent any contamination of the laser optics. In the same location there is also installed the remote I/O for the LINDARC™ – PLC communication.

1.3 Automation Overview

To store and manage the data provided by the LINDARC™ system, and use them inside a dynamic process control logic, the system is connected to several devices as indicated in the Figure 6.

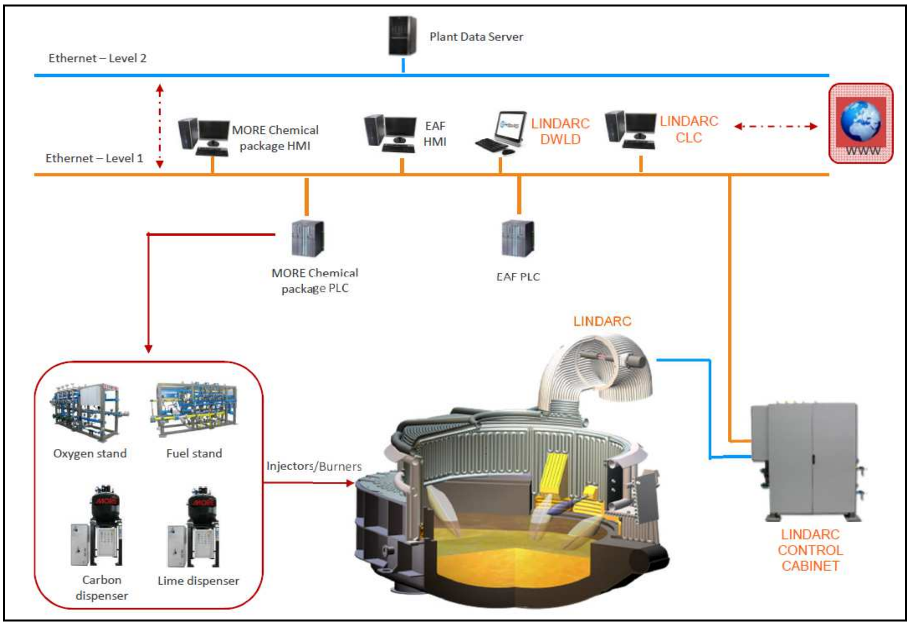

Figure 6: Automation network

The automation system includes a LINDARC™ Control Computer (LCC) with dedicated Human Machine Interface, Closed Loop Control (CLC) and Dynamic Water Leak Detection (DLWD) software. EAF and off-gas measurement data are stored into a SQL server and a powerful database is used to analyse historical process data, that can be performed locally or on remote computers via Internet or Intranet connections.

1.4 Dynamic Process Control

The advantages of the TDLAS technology versus the conventional extractive devices has been already underlined extensively in previous papers [4,5] as well as the reliability and maintenance friendly high levels, so this paper focuses only on the strategy adopted in this installation to fully benefit from the knowledge provided by the continuous off-gas measurements performed by the LINDARC™ system.

1.4.1 Post combustion during the melting phase – closed loop control and optimization strategy

The basic idea about post combustion inside the EAF is to promote the combustion of the unknown hydrocarbons (oil, paints, grease and plastics) introduced in the furnace together with the scrap charge. The melting phase (solid scrap) is the most favourable phase to perform this task because the combustion products can get in contact with a large scrap surface and the temperature gradient between the hot gas and the same surface is maximized; both these aspects are key factors to achieve an efficient energy heat transfer to the scrap pile that leads to a power on time and electrical energy usage reduction.

Before the advent of the off-gas measuring technologies the only way to perform this was to add extra oxygen to the stoichiometric one necessary to achieve the complete combustion of injected natural gas. Even if this practice was, and still is, widely diffused among steelmakers it could have a negative effect on several key performance parameters such as: the electrode, the carbon and the oxygen consumptions and most important the metallic yield. The reason for these drawbacks is that the request for the extra oxygen, from now defined as post-combustion oxygen, is embedded in the burner mode firing profiles in use without the exact quantitative knowledge of CO and H2 freeboard levels in the EAF at any given time. Using a trial and error approach, furnace supervisors develop their own burner profile that normally is a guess on how much post combustion oxygen has to be injected.

Figure 7 shows clearly that CO evolution is not a steady value; for example at 20% of scrap bucket melting, the average CO concentration is 11.7 %Vol. wet, with a standard deviation – σ – of 5.5 % Vol. wet; when looking at distribution the CO levels are quite different from one heat to another.

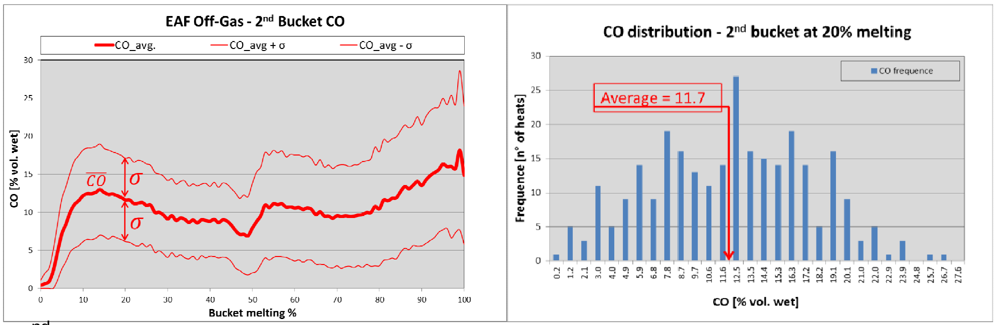

Figure 7: 2nd bucket CO trend and distribution based on 279 heats with same scrap mix and burner profile.

This inherent variability of CO weakens the traditional approach for post combustion oxygen to be part of the burner mode profile; in this way the right amount of oxygen is seldom injected at the right time, meanwhile there is a real risk to overblow when the CO levels are low, leading to excessive charge oxidation and increase of the electrode, oxygen and carbon consumption. On the other hand, when CO level is high, the failure to deliver post combustion oxygen does not allow to fully exploit this energy source and leads to increase CO emissions into the atmosphere.

The only feasible way to overcome this problem is to drive the post combustion oxygen increase/decrease to the oxidation degree of the EAF atmosphere.

LINDARC™ technology provides reliable and fast response time gas measurements and, via an algorithm named Closed Loop Control (CLC), is able to transform these information into targeted feedbacks to adjust burners oxygen/natural gas ratio following the real time furnace atmosphere oxidation level.

A key factor of this dynamic control is the very fast response time guaranteed by the laser based technology. Long response time achieved by traditional extractive measurement technologies can lead to a bad timing between the real CO evolution and the post combustion injection (Figure 8). LINDARC™ response time of 2 seconds is fully adequate to deal correctly with this issue.

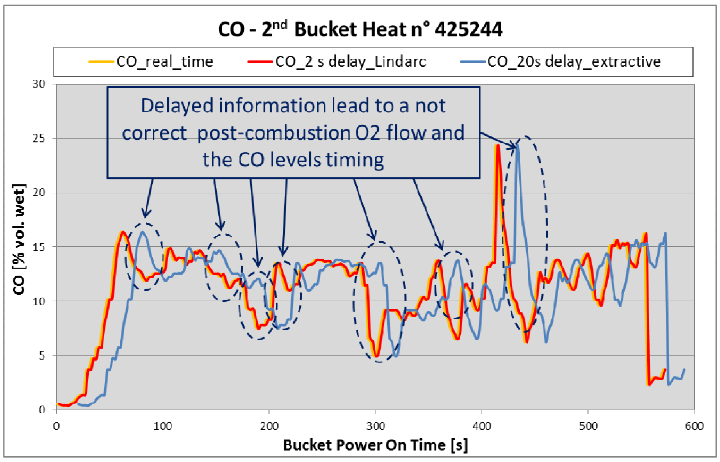

Figure 8: Instantaneous CO with different response times

A specific algorithm has been developed to translate the information provided by TDLAS technology into proper injection set points for the post combustion oxygen.
And it's used to assess the oxidation level of the furnace atmosphere. The higher the PCD the lower the burners oxygen-natural gas ratio will be, with the lowest limit defined by the oxygen-natural gas ratio set in the burner profile. The software code, has the possibility to operate both in O2 mode, where the oxygen-natural gas ratio is changed by the oxygen flow increase/decrease, and CH4 mode, where the ratio is changed modifying the natural gas flow.
Due to this, the Human Machine Interface software has the possibility to include or exclude from the post combustion algorithm any burner as well as limiting the phase during which the post combustion has to be performed.
Even if the TDLAS technology actually is not able to provide the H2 measures (the H2 molecule has the electronic energy transition in the UV region where laser diodes operating at room temperature actually are not available) a good correlation with the CO, especially during the melting phase, has been found (Fig.10).

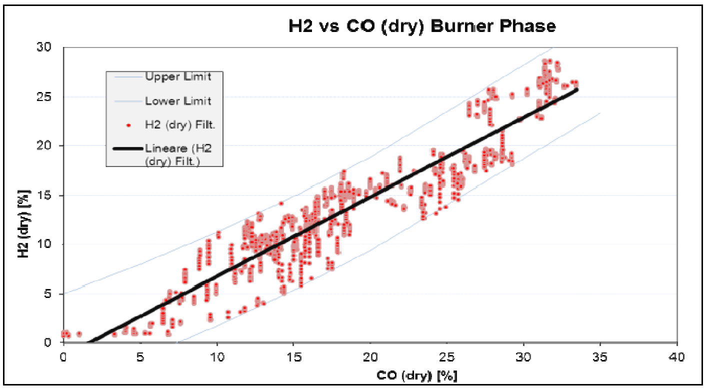

Figure 10: Example of H_2-CO correlation

To customize this linear correlation for every installation, during technology commissioning, the H2 measurement is done using an extractive probe together an H2 thermal conductivity analyser.

1.4.2 Dynamic water leak detection

Another application of LINDARC™ technology is the detection of abnormal high water vapour content in the EAF off-gas, which reflects an increased risk of a water leak inside the furnace vessel.

Unfortunately, in the EAF process, the water leaks are not the only source of water vapour and among the main sources of water vapour can be counted:

- Combustion of the known hydrocarbons (injected natural gas, volatile matter of the injected/charged carbon), and the unknown hydrocarbons (plastics, oils, grease contained in the scrap charge).
- Electrodes cooling water.
- Rain and snow embedded into the scrap charge.

Furthermore the dilution effect of secondary air ingress (through door, roof ring and elbow) can modify significantly the H2O concentration in the EAF shell atmosphere.

Due to those factors the statistic approach is the only one feasible to determine the threshold above which the water vapour content has to be considered abnormal. An algorithm, developed by MORE, takes into account several aspects that can lead to a change in the water vapour content normal trend, and build proper water vapour benchmarks to be selectively applied based on different parameters:

- Scrap mix and/or steel grade
- Heat total number of buckets.
- Bucket number.
- Cold start heat or other unusual conditions.

Two thresholds (Fig.11), indicating different levels of risk of water leak, are based on the EAF power on time. A moving horizon statistic method is used to update these thresholds, to take into account the fluctuations of the scrap contained hydrocarbons and weather conditions in the scrap yard. A gradual increase of the water content due to rain or snow, as well as an higher amount of paints/plastics inside the scrap pile are promptly taken into account in the data set used to evaluate the thresholds.

Once the actual H2O content crosses one, or both thresholds, the algorithm starts to compute a so-called "gravity index" which takes into account both the duration and the gravity of the threshold crossing. In order to avoid false positive alarms (warning without any water leak presence), only when this gravity index reaches a high value a warning message (visual and acoustic) is triggered to alert the furnace operators.

05:31:26:196 Ora bit inizio colata
06:25:31:374 Ora power ON
Numero 12567
Gruppo 0
Ceste 1
Ora bit fine colata 00:00:00:000
RX data Real
52.963
46.114
24.000
CO2 Laser % segnale 77.00
CO Laser Temp °C 927
Contatore valori H20 invalidi 0
Percentuale valori H20 invalidi 0
Allarmi 1° soglia (H) 00
Allarmi 2° soglia (HH) 00

Figure 11: Dynamic Water Leak Detection furnace operator screen

1.4.3 Operational results

LINDARC™ system has been in operation at ABS furnace since September 2014. Hereinafter are key operational results achieved till now.

1.4.4 Post combustion – closed loop control and process optimization

To make an assessment of post combustion performance's gains a benchmark has been created running the EAF for more than 500 heats with post combustion CLC disabled and with LINDARC™ system collecting off-gas data so to take a picture of this particular process and then develop the correct strategy to perform post combustion. During this period the data showed a clear distinction on terms of CO levels between different scrap mixes (Fig.12); as a result the post combustion CLC has a different impact on each scrap mix.

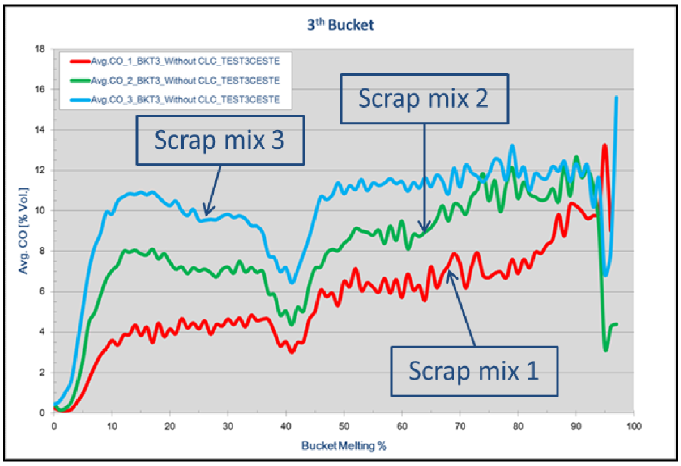

Figure 12: CO level for different scrap mixes

After the performance benchmark has been established the CLC for the post combustion has been enabled for 330 heats considering, in terms of scrap mix, the same number of heats percentage so to obtain two comparable campaigns. Here below are achieved results (Tab.2); referring to metric ton of liquid steel measured in the ladle after tapping.

Table.2: LINDARC^{TM} operational results

Dynamic Post Combustion Closed Loop Control (CLC) – Operational			
Parameter	Benchmark (without CLC)	With CLC	Difference
Electrical energy	*417.5 kWh/t*	414.4 *kWh/t*	**- 3.1 kWh/t**
Power On	*42.2 min.*	41.4 min.	**- 0.4 min.**
Oxygen	*28.1 Nm^3/t*	28.3 Nm^3/h	+ 0.2 Nm^3/h
Injected Carbon	*11.8 kg/t*	10.8 kg/t	**- 1 kg/t**
Charged Carbon	*3.8 kg/t*	3.3 kg/t	**- 0.5 kg/t**
Tapping Temp.	*1690 °C*	1692 °C	+ 2 °C
Yield	*92.4%*	93.8%	**+ 1.4%**

The differences between the benchmark and CLC test period lay on the way extra oxygen has been injected. In the first group of heats, (without CLC), post combustion oxygen was determined by the level 2 burner profile (static mode), whereas with CLC enabled the level 2 profile was stoichiometric and the post combustion oxygen was determined by Post Combustion Degree (PCD) from LINDARC™ measurements. The dynamic capability to choose the right time and quantity of post combustion oxygen, based on the oxidation level, allowed an improved energy recovery from the combustion of fuels in the EAF freeboard (Fig. 13).

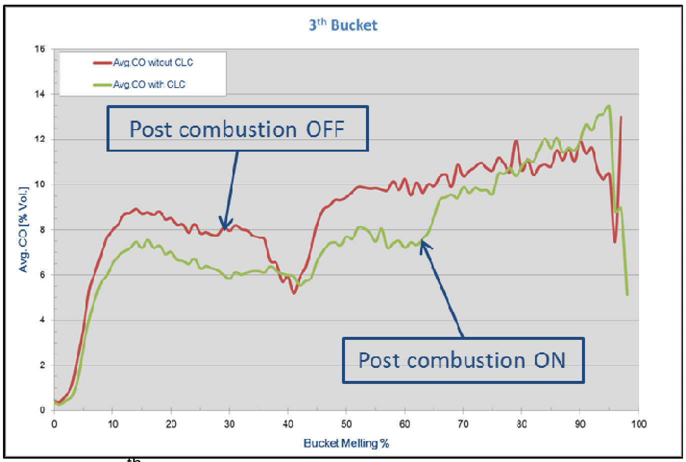

Figure 13: 3th bucket, CLC period vs. no CLC period CO trend

Another primary aspect to be considered is the reduction of carbon consumption and the metallic yield improvement. Post combustion oxygen dynamic control, achieved with LINDARC™system, allowed to minimize metallic oxidation leading to reduction of injected/charged carbon and more important to improvement of the metallic yield.

1.4.5 Dynamic water leak detection

After period of data collection, the water leak detection algorithm has been enabled, generating warnings confirmed by the presence water leaks inside the EAF (Fig.14-15). Some leaks (the smaller ones) occurred during furnace operation were not catch due to the strong variance of $H2O$ signal and intrinsic difficulty of a statistic approach which has to maximize its sensitivity and, in the same time, minimize the false warnings. The parameters of the algorithm are still under fine tuning to determine the best compromise between water leak detection versus false warnings minimization.

Figure 14: High Warning for water leak generated on EAF operator screen

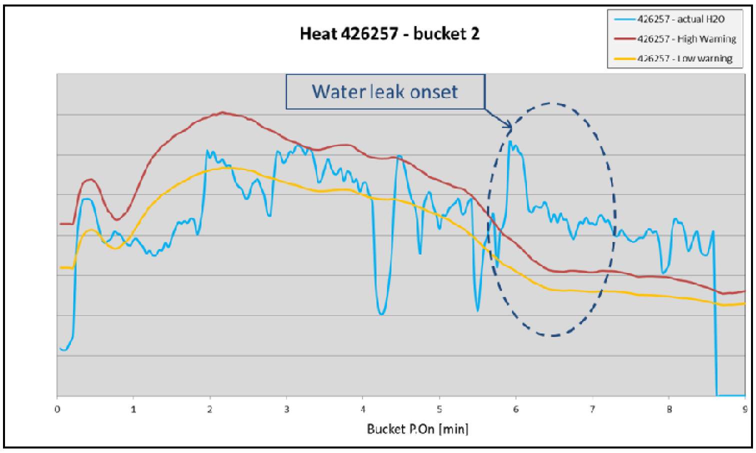

Figure 15: Data post process showing the water leak onset on a different heat.

1.4.6 Transmission signal

Even if it is not a direct process performance index, a good laser transmission signal is a must for every TDLAS system to generate reliable and consistent off-gas measures. The biggest challenge for this technology, when installed immediately downstream the 4th hole elbow, is the off-gas high dust load and duct vibrations that could lead to transmitter/receiver misalignment. There is a critical low transmission value under which the measure is not reliable or not available at all. Hereinafter the analysis of the transmission for both periods where is clearly shown the negligible amount of time with transmission signal below the critical value.

1.5 Q3INTELLIGENCE for Process Monitoring and Control

1.5.1 Off-line trend analysis

To extract useful and robust information from the vast amount of measures made available by the LINDARC™ analysis system and the existing process automation system, a smart and flexible data analysis engine must be deployed. In order to properly characterize and contextualize the process, advanced data acquisition, normalization and storage procedures were implemented by Danieli Automation on Q3Intelligence platform. The result is an Excel-based, fully customizable analysis tool which is able to process huge amount of data (full process trends of thousands heats) and to extract average and deviation trends in a matter of seconds. Process technologists may select among all relevant variables made available also by the off-gas probe to correlate them with different practices, charge recipes, heat energy, duration classes and raw materials used.

Trends are determined as function of process time or specific energy in terms of average and standard deviation band.

The system performs the following operative steps:

- Acquisition
- Filtering
- Trend evaluation

Such trends represent the “fingerprint” of the process

1.5.2 On-line trend-based process monitoring and control

By means of the insights provided by the off-line analysis tool, the best filtering and pre-processing strategies have been isolated to be implemented in an on-line application for process monitoring and control. This process supervisor uses the same data storage model to quickly extract the expected process trends and compare them with the current conditions, identifying deviations and providing a robust base for process control such as oygen injection control during the refining phase.

Both the offline and online modules are currently under trial and in a short time they will be able to evolve the static melting profiles to the best performing and adapted to the ever-changing scrap based steel production.

The system will also adjust dynamically the carbon boil through decarburization by oxygen modulation in order to obtain the final steel composition with minimum iron loss.

2 CONCLUSION

The laser off-gas analysis system nowadays has to be regarded as an unique source of knowledge about EAF process improvement. LINDARC™ technology, with associated algorithms for post combustion optimization and water leak detection, has proven to be an effective tool to make EAF steelmaking process more efficient and safer. The possibility to drive dynamically post combustion oxygen leads to important savings related to electrical energy and carbon consumptions and metallic yield improvement.

Priceless is the contribution to safety due to water leak detection capability used to put in place practices much safer for operators and equipment.

Other applications where LINDARC™ system can have a successful application are:

- To prevent explosions in the dust settling chamber or bag house, dynamic control of the combustion gap/dumper position.
- Carbon injection dynamic control.
- Carbon credits by the reduction of the environmental footprint.

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